Research Needs

SALT MARSH RESTORATION, REHABILITATION, AND CREATION TECHNIQUES FOR CALTRANS CONSTRUCTION PROJECTS

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The purpose of this report is to discuss aspects of salt marsh mitigation to determine information and data needs that are necessary to develop more effective [illegible] methods occur in the areas of 1.) hydrodynamic process, 2.) soil development, 3.) vegetation establishment, 4.) monitoring, 5.) spatial requirements, 6.) construction and equipment, and 7.) stormwater treatment.

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Research Needs

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EXECUTIVE SUMMARY

The California Department of Transportation (Caltrans) currently is mitigating, or proposing to mitigate, the loss of coastal salt marsh habitats due to highway improvements by replacing, enhancing, or constructing new saltwater marshes. The purpose of this report is to identify information and data needs that are necessary to develop more effective methods and techniques for the enhancement, restoration, or creation of saltwater wetlands and marshes. In reviewing the material presented in this document, it is important to remember that the objective is to define those research needs that will allow Caltrans to carry out its mission more effectively, and not to identify all of the research needs associated with salt marsh restoration.

While a considerable amount is currently known about coastal salt marshes, much more information is needed before successful salt marsh restoration and creation projects can be carried out reliably. Additional research is required in the following areas: (1) hydrodynamic processes, (2) soil development, (3) vegetation establishment, (4) monitoring, (5) spatial requirements (6) construction and equipment, and (7) stormwater treatment. The importance of these areas is underscored by the relationships between each process. The provision of proper marsh hydraulics will insure effective soil development which in turn leads to an adequate nutrient supply for plant establishment and a healthy ecosystem. Insightful planning and the determination of suitable construction methods will increase chances for restoration success and the protection of existing resources. Specific research needs are identified in the text of this report.

HYDRODYNAMIC PROCESSES

A clear understanding of marsh hydrodynamics is essential to the restoration process. Prediction of flow patterns and rates, channel sizes and locations, and sedimentation rates sets the stage for the ability to implement chosen design parameters and to insure proper soil development and successful plant establishment . The primary hydrologic components that effect a marsh include tidal flows and freshwater flows in rivers and creeks. Hydrodynamic models developed for a marsh system should incorporate a number of critical variables. Flow rates and velocities should be estimated in flow channels and across the entire marsh system for daily and seasonally changing tidal and freshwater flows. The effects of marsh hydrodynamics on salinities, suspended sediment loads, water

temperature, and pollutant loads should also be considered to obtain an accurate representation of the marsh hydrology.

SOIL DEVELOPMENT

Natural saltwater marsh soils are deposited onto the marsh plain by tidal flows or river flows. Prediction of sedimentation rates is important in establishing a time table for marsh development. When a marsh is restored by reintroducing tidal action or when a marsh is created from an upland area with existing or imported soils, the initial characteristics of the soil are quite different from a mature marsh soil. Little is known about how long it takes for an undeveloped marsh soil to stabilize or how to create a marsh soil using existing or imported soils. Where dredged materials have been used to raise elevations, highly acidic soils have developed due to limited tidal flushing. Oxidation and the formation of sulfuric acid occurs when the sulfide rich anaerobic soils are drained and exposed to air. Salt marsh plants are unable to grow in low pH soils. Efforts to correct acidic soil conditions have included the application of lime, but more research is needed into effective amounts and methods of application.

VEGETATION ESTABLISHMENT

Several salt marsh plant species, particularly *Salicornia sp.*, readily colonize west coast salt marsh areas without help from man, but getting other plant species, most notably *Spartina foliosa*, to inhabit newly created marsh sites has proven to be more difficult, often requiring manual planting methods. An extensive amount of research on transplanting and seeding *Spartina sp.* has been conducted on the East Coast. The few transplanting and seeding projects that have been conducted on the West Coast have had only limited success. Exactly what needs to be done to achieve greater success in establishing different types of vegetation is unclear, but it is clear that there is considerable room for improvement. More research is needed to determine the environmental requirements of various marsh species and how the requirements differ between regions in California.

MONITORING

Without an effective monitoring program, degradation of a restored marsh could occur and the success or failure of the mitigation project may never be determined. Proper monitoring can be used to anticipate potential marsh changes so that corrective maintenance can be done before serious problems develop. To be effective, marsh monitoring programs should record information prior to, during, and after construction. Research is needed to determine the parameters that will provide the most useful information and a proper length of time for restoration assessment.

SPATIAL REQUIREMENTS

Proper planning and design of marsh restoration or creation projects is crucial to their success. Details regarding the type of marsh or wetland to be developed should be well thought out and delineated. The topography of the marsh, including the distribution of open water, tidal zones, and upland habitat is critical for a self-sustaining system. The appropriate areal and elevational parameters for each zone should be considered along with provision for a buffer zone between the marsh and adjacent populated areas. More needs to be known about the minimum sustainable size of a marsh; the optimum distribution of upland, tidal and open water habitats; and the minimum buffer zone size and type.

CONSTRUCTION AND EQUIPMENT

Because marsh restoration and construction is a relatively new field, optimum methods and equipment are still unknown. Saturated marsh soils are typically very soft and do not support heavy equipment. When used, heavy equipment can cause soil compaction problems that make vegetation establishment difficult. Equipment used for maintenance should be chosen carefully because marsh ecosystems are easily disturbed. In those instances where a marsh is created from an upland or dry area and then introduced to tidal flow, conventional equipment can be used, but compaction and scarification (surface scraping) problems may arise.

STORMWATER TREATMENT

The ability of freshwater marshes and wetlands to remove pollutants effectively has been well documented. Marshes located on the fringe of estuaries serve as natural water treatment systems that help protect the estuaries from overloads of nutrients and other pollutants. Today, most coastal salt marshes serve as stormwater treatment systems simply because of their location in relation to urban development. When designing a salt marsh it is important to understand the ability of plant and animal species to cope with potential pollutants.

1
INTRODUCTION

The California Department of Transportation (Caltrans) currently is mitigating, or proposing to mitigate, the loss of coastal salt marsh habitats due to highway improvements by replacing, enhancing, or constructing new saltwater marshes. However,the present state-of-the-art salt marsh restoration/construction is not well-defined scientifically. Appropriate design and construction methods are not known for all habitat types, and a reliable set of design and operating criteria is not available to make decisions on proper management procedures. An essential goal, one that has been overlooked in the past, is to make the restored marsh as self sufficient as possible. The most successful project will be one in which available hydrodynamic and ecological forces are utilized in the maintenance of the system. The inclusion of sophisticated machinery and narrow operating parameters is usually based on an assumption that funds and knowledgeable, responsible management will be present into perpetuity to maintain the system. It is impossible to predict whether these expectations will be met.

The University of California has undertaken the development of a series of four design manuals for marsh restoration and enhancement. A manual will be prepared for each ecoregion of the California coast as defined by Caltrans: Southern California, Central California, Northern California, and San Francisco Bay. The ecoregion of Southern California covers the portion of coastline between the Mexican border and Point Concepcion. The Central California region extends northward from Point Concepcion to Bodega Bay. North of Bodega Bay to the Oregon border is the Northern California Region. The remaining brackish and salt marshes are located in the San Francisco Bay region. Based on a careful assessment of information contained in the literature, it is clear that there are several areas of salt marsh restoration where further knowledge is needed to make salt marsh design, construction, and management more successful and reliable.

PURPOSE

The purpose of this report is to identify information and data needs that are necessary to develop more effective methods and techniques for the enhancement, restoration, or creation of saltwater wetlands and marshes. In reviewing the material presented in this document, it is important to remember that the objective is to define those research needs that will allow Caltrans to carry out its mission more effectively, and not to identify all of the research needs associated with salt marsh restoration.

SCOPE

The study described in this report involved: 1) the conduct of an extensive literature search, 2) site visits to several marshes in northern and southern California, and 3) discussions with workers in the field of marsh restoration. The principal focus of the study was to identify research needs.

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In addition, the following experts in salt marsh restoration also provided valuable comments on the report and helped make it a better and more comprehensive document: Dr. Robert Coats and Dr. Jeffrey Haltiner, Philip Williams & Associates, Ltd.; Dr. Michael Josselyn, Professor, San Francisco State University; and Dr. Joy Zedler, Professor, San Diego State University.

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SALTWATER MARSHES

The purpose of this chapter is to introduce the reader to development of natural salt marsh systems and to the important processes that affect their development. The impact of catastrophic events and the effects of anthropogenic influences are also examined briefly.

DEVELOPMENT OF COASTAL SALT MARSHES IN CALIFORNIA

The principal natural processes that effect the development of salt marshes involve hydrodynamics, geomorphology, and biological succession. Depending on the source of the sediment, there are two principal types of salt marshes along the California coast. In the first type of marsh, which develops along the shores of bays, the sediments are supplied throughout the year by tidal action. In the second type of marsh, which develops near the mouths of rivers, the sediment is provided by river flood flows during the rainy season. Each of these types of marsh, and the natural processes that effect salt marsh development, is considered separately in the following discussion.

Marshes formed along the shores of bays

Estuaries that include shallow bays, such as the San Francisco Bay system, receive sediments from rivers during winter and spring when river flows are greatest. It has been estimated that about 90 percent of the annual amount of river borne sediment deposited in San Francisco Bay arrives in 10 percent of the time. Suspended sediments that enter large bays or estuaries are deposited in the upper reaches of the bay or estuary due to the combined effects of decreased velocities and mixing with saltwater. Subsequently, the sediments are resuspended throughout the year by wind, wave, and tidal action and deposited on marsh surfaces.

Daily onshore winds during spring and summer generate waves that suspend sediments in the shallow bays that were deposited during the winter. Tidal currents circulate the suspended sediment during late morning and afternoons while the wind blows and it settles at night when the wind subsides. Repeated deposition and suspension with tidal currents results in continual circulation of suspended sediment. The suspended sediment is gradually lost to the ocean, to marsh surfaces, and to locations in the estuary where waves or tidal currents cannot resuspend it (Krone, 1985).

Sediments accumulate in areas along the shores of bays that are protected from wind and wave action. Deposition continues until the elevation of the mud is raised high enough to be exposed during low tides. The surface of these newly developed mudflats is often stabilized by the growth of algae. As the mudflats continue to increase in elevation, ebbing tidal flows cut intricate drainage channels into the mudflats (Pestrong 1965). *Spartina foliosa* (cordgrass), which is able to withstand the salinity of sea water and longer periods of water inundation than other marsh plants (Mahall and Park 1976), can become established in the soft, fresh, nutrient rich mudflats. During tidal flooding, as sediment laden water flows through stands of *S. foliosa*, mild velocity gradients are created causing the suspended sediments to aggregate and settle out. The presence of plants greatly increases sedimentation and a marsh plain begins to develop. Plants also protect the deposited sediments from wave action (Krone 1982).

As sediment accumulates and the marsh plain elevation rises, the frequency and duration of tidal inundation will decrease and the rate of sediment deposition on the marsh surface slows. However, the rising sea level tends to increase the frequency and duration of tidal inundation and the elevation of the marsh seeks a level relative to the tidal datum that is determined by the suspended solids concentration of the flooding waters (Krone 1982). As the elevation of the marsh rises to a level where other plants can compete with *S. foliosa*, other types of salt marsh vegetation, particularly *Salicornia virginica* (pickleweed), begin to inhabit the higher areas of the marsh. The establishment of vegetation on the marsh plain serves to stabilize marsh channels (Pestrong 1965). When the marsh vegetation becomes well established microorganisms, crustaceans, and insects become more plentiful within the marsh. These fauna, as well as the marsh vegetation, are important food sources for many birds, fish, and mammals.

Marshes formed at or along the mouths of rivers

In general, most California salt marshes are confined to narrow stream outlets along the coastline. Marshes such as Upper Newport Bay and Tijuana Estuary receive the bulk of their sediment directly from flooding by river flows (some floods may be characterized as "catastrophic", see below) during a brief winter wet season and only limited amounts by tidal action. A small portion of the sediment load is deposited on the marsh surface and the remainder is carried into the ocean where it is lost over the deep ocean shelf or to littoral transport. Aside from the differences in sediment supply, the natural processes that govern salt marsh development apply to the two different types of salt water marshes described above as well as marshes that have combined sediment inputs (freshwater and saltwater).

EFFECTS OF CATASTROPHIC EVENTS

Catastrophic events are particularly important in the life of a marsh. An extremely large storm can restructure a marsh system by destroying vegetation and significantly altering the marsh topography. Large storm floods can also alter soil salinities and affect seed germination, which in turn can affect the distribution of vegetation (Zedler 1982). Before man began to alter natural marshes and their upland watersheds, marshes were cleansed and renewed periodically by large storm flows that scoured the marsh surfaces and channels and delivered fresh supplies of sediment (Zedler 1982). Because of erosion in upstream watersheds, extreme storm events may contain too much sediment and fill in much of the marsh. Alternatively, dams have greatly reduced the sediment supply to some marshes. Many marshes that now exist along the California coast are protected from catastrophic changes by upland flood control and water diversion structures.

ANTHROPOGENIC INFLUENCES

Virtually every coastal wetland in the state of California has been affected by the presence of man. Perhaps the most common alteration is the construction of barriers, such as roads and levees, either through or along the periphery of marshes. Man-made boundaries may intersect marshes and prevent many animals from migrating to different areas within the marsh and from moving to upland areas when marsh floods occur (Shellhammer et al. 1984). When roads and levees are constructed within marshes, culverts are often used to maintain tidal flows into and out of the marsh. Because culverts alter marsh hydrodynamics significantly, their presence can change the ecology of the marsh.

Other anthropogenic disturbances include housing and commercial developments that are built adjacent to the marsh. Implementation of such developments often destroys the buffer zone (the transition zone to upland habitat that separates the marsh from the activities of man and provides higher ground and cover during flooding) that many animals and birds need for protection (Shellhammer et al. 1984). Often the developments extend into the marsh, replacing much of the original marsh area. Diking or filling the landward portions of a marsh reduces the volume of water that floods the marsh during high tides. The reduction of flow through the remaining length of slough channels facilitates deposition. The channels gradually fill with sediments and marsh plants until they reach cross-sections that can be maintained by reduced flows.

Wastewater discharges, industrial discharges, and stormwater runoff often contain large quantities of nutrients and other pollutants that can alter a marsh ecosystem.

Wastewater discharges can change the salinity and nutrient loading within the marsh, while industrial discharges may contain other pollutants. Stormwater runoff may contain high concentrations of fertilizers and pesticides in agricultural areas and may contain high concentrations of heavy metals, greases and oils in urban areas.

Several other anthropogenic activities have had varying effects on salt marshes. The natural function of a marsh may be altered by upstream diversions of fresh water inputs or by channelization of creeks and rivers for flood control (Speth et al. 1970; MacDonald 1976a). As mentioned above, upstream water diversions and flood control structures may protect the marshes from catastrophic events and, therefore, alter the natural development of marshes. Alternatively, construction and logging activities may cause excessive erosion in upstream watersheds, which may fill in marsh areas. Invasion of the marsh by non-native plant species is another serious impact resulting from the activities of man. Groundwater pumping has caused some marsh areas to subside around South San Francisco Bay (Krone 1982).

As a consequence of the activities of man, most of California's saltwater marshes that are in existence today do not function as they did in the past. The fact that most marshes do not function as they once did is a critical factor that must be recognized and considered when restoring degraded marshes and creating new marshes.

3
HYDRODYNAMIC PROCESSES

Transport of water into and out of a salt marsh is vital to the health and successful development of the entire salt marsh ecosystem. Hydrodynamic processes control sedimentation, erosion, salinity, temperature, and nutrient supply. The overall effect of these processes on marsh evolution is proving difficult to predict in restoration projects. The discussion in this and the following sections is presented from the standpoint of what needs to be known to design and implement marsh restoration and creation projects.

BACKGROUND

A clear understanding of marsh geomorphology is essential to the improvement of marsh restoration results. At present, it is difficult to predict where channels will develop and in what direction a marsh might expand. Records of marsh attributes that can be used to predict how marshes develop are available for only the previous hundred years at best. More information is needed on the process of marsh channel formation, functional surface slopes, and the effect of flow patterns on the distribution of plants and animals. Hydrodynamic models are becoming an integral and invaluable part of the restoration design process and are being used to predict marsh channel flow rates, patterns of flow, and changes in the marsh surface. Without the ability to model flows and sedimentation rates, errors with far reaching consequences can be made in the design process. The flow of water and the flushing action of the tides are essential to the support of life in the marsh. The construction of an inadequately sized channel can lead to loss of marshland. The inadvertent creation of stagnant pools can become mosquito breeding sites and a source of odors.

The modeling of marsh hydrodynamic processes is in its infancy, and improved methods of analysis and computer hardware are being developed as knowledge increases. Great strides have been made from black box models of inputs and outputs, where no information is known about the processes occurring within the system, to the present numerical solutions of St. Venant and Navier-Stokes equations. However, verification of predicted conditions is needed to expand and refine models for more effective use in the future. Difficulties in acquiring data for model input and verification of results have limited the evaluation of models. Naive application of models can give the user a false sense of security, be seriously misleading if an important aspect is overlooked, and encourage designs that can be modeled over other, possibly better, designs that can not be modeled easily (Coats et al. 1987). While many improvements of models are desired, their use is already essential to the design of hydrologic environments that will sustain a healthy marsh.

Models should be selected and applied with clear understanding of their value and limitations. Adequate and reliable data on the geometry of the marsh, tides and/or river flows, and suspended solids concentrations must be generated for use with the models. Project requirements will determine the type of model to use. If an approximation by channel flow is sufficient for design purposes, a one-dimensional (1-D) flow model, such as a link node model, may be adequate. If the flow across a marsh is required, then use of a two-dimensional (2-D) model may be necessary. Representative hydrodynamic models that have been used to predict marsh flows, water surface elevations, and sedimentation rates are presented in Table 3-1 along with the required input data and limitations.

ISSUES

The factors that must be addressed in an effort to understand the evolution of a marsh with respect to hydrodynamic processes include: marsh hydraulics, sedimentation and erosion, marsh geometry, effect of hydrodynamics on water quality, and the impact of human activities. Each of these topics is considered in the following discussion.

Marsh hydraulics

Marsh hydraulics are governed by tidal forces. Tides affect shoreline erosion, modification of bottom characteristics, formation of sand bars, and patterns of currents in bays and estuaries (Clark 1983). Patterns of flow within the marsh control the transport of sediments, detritus, seeds, and propagules and thus affect marsh expansion and development. Tidal ebb and flow create an efficient flushing system to prevent the buildup of excess nutrients, periodically cleansing and rejuvenating the marsh system. Duration and inundation of tides are important in the distribution of plant and animal species within the wetland (Mall 1969; Zedler 1982).

In California there are two unequal tidal cycles per day. Tide heights are predicted and printed by the National Oceanic and Atmospheric Association (NOAA) in the yearly publication *Tide Tables, West Coast of North and South America*. Higher and lower than average tides occur twice monthly (spring and neap tides) and yearly. Tide heights vary with locality and must be measured, or modeled from other tide data, at every restoration site. Mean higher high water (MHHW) and mean lower low water (MLLW) are the daily extreme conditions that are averaged by NOAA over a tidal epoch. The volume of water

Table 3-1
REPRESENTATIVE HYDRODYNAMIC MODELS THAT CAN BE USED FOR WETLANDS MODELING AND THE DESIGN OF RESTORATION PROJECTS

Model	Advantages	Parameters	Limitations
Link node (1-D) using St. Venant equations (Krone 1982)	Flow through channels, water surface elevations	Elevations, channel dimensions, tidal cycles, friction coefficients	Short channels require small time step
(Krone 1985)	Marsh surface elevations	Suspended sediment concentrations, particle size distribution, tides, historic sea levels, dated cores	
RMA 2-V (2-D) (Roig 1989)	Water surface elevations, 2-D velocity vectors	Turbulent exchange coefficients, friction coefficients, elevations, channel dimensions, tidal cycles	Expensive to run for long simulations
STUDH (2-D) (Thomas et al. 1985)	Marsh and channel bed elevations, suspended sediment loads	Suspended sediment concentrations, particle size distribution, currents, water surface elevations, water velocities	Expensive to run for long simulation periods
MPOND (Coats et al. 1987)	Water surface elevations	Characteristics of culverts and water control structures, tide cycles, runoff hydrographs, elevation and storage capacity for each pond	Only applicable to relatively small enclosures of water

that flows in and out of the marsh between MHHW and MLLW is called the mean diurnal prism. In many riverine marsh systems in California, ocean entrances can become blocked by littoral transport. A sufficiently large tidal prism is needed to maintain the entrances and to provide adequate flushing of the marsh (Zedler 1982; Mudie et al. 1974, 1976).

Relative sea level rise along the United States Coast has averaged about one foot over the last one hundred years (U.S. Environmental Protection Agency 1989). The ocean level at the Golden Gate Bridge has risen slightly more than 0.6 ft (0.2 m) during the same period. Predictions of a continuing increase for the United States Coast range from 1.5 to 7.0 ft (0.5 to 2.1 m), due to global warming and associated ecosystem changes (U.S. Environmental Protection Agency 1989). Serious questions are being raised regarding the stability of existing marshes. If the rate of sea level rise is constant and there is an adequate supply of sediment, marshes will attain a steady relative elevation (Krone 1982). In most cases, a shortage of upland buffer zone precludes marsh expansion in response to sea level rise. Design of new and restored marshes will have to include predictions of sea level rise and mechanisms to prevent wetland loss. For example, a restoration project at Carpinteria Marsh in Ventura County is being designed for a 3 to 6.5 ft (1 to 2 m) sea level rise. Upland habitat is being planned in anticipation that it will be converted to wetlands during the rise in water level (Ferren 1989).

Sedimentation and erosion

It has been observed that *Spartina foliosa* prefers soft, fresh sediments for initial establishment (Krone 1982). An important design objective is to utilize, wherever possible, existing sediment transport mechanisms to provide essential substrate for the establishment of vegetation. The rate of sedimentation is dependent on the concentration of suspended solids in tidal and fluvial flows. Mathematical models that have been used to predict sedimentation rates are listed in Table 3-1. Where on-site data are not available, sedimentation rates can be estimated by modeling the observed deposition in nearby small craft harbors with consideration given for extreme flooding events. Provision of favorable conditions for natural sedimentation will insure greater success in seeding and planting operations.

Channels that are too small for existing flow conditions can be subject to erosion, especially if they contain sandy bottoms (Haltiner 1987). Erosion is not as great when channel bottoms are comprised of cohesive sediments and constrictions within the marsh may develop if the channels are designed or mistakenly built too narrow. Channels should be designed to accommodate extreme conditions as well as normal daily flows.

Marsh geometry

The sizing, placement and degree of branching of channels are all very important to the effective conveyance of water through the marsh. Sloughs or higher order channels convey tidal flows between the estuary and the marsh. Lower order channels carry water from the primary slough to the far reaches of the marsh during flood tides and drain the outer reaches during ebb flows. Philip Williams and Associates, a well known firm in the design of salt marsh restoration projects, tries to create a tidal drainage system of multiple order channels. The lower order channels should meander naturally and be sized to convey the appropriate tidal prism. The spacing of channels should be designed to ensure that no point on the marsh surface is more than about 100 feet from a channel or a slough. Slough junctions should be approximately 120 degrees and intersections of channels and sloughs should be close to 90 degrees (Haltiner 1987). Width, depth, and side slopes of channels are determined by the necessary flow capacity, the type of vegetation that will be established along the banks, and the amount of marsh flooding desired. The natural evolution of marsh channels is considered in detail in "The Development of Drainage Patterns of Tidal Marshes" (Pestrong 1965) and "Geomorphic Processes of an Estuarine Marsh: Preliminary Results and Hypotheses" (Collins et al. 1987).

Overall marsh surface elevations are critical to the establishment of a diverse community of organisms. Salt marsh plants exist in a very narrow elevation band and a six inch elevation error during grading can affect the establishment of some species (Haltiner 1987). The slope of Tijuana Estuary is 1 percent and it has been recommended that a 1 to 2 percent grade be maintained in restoration projects (Zedler 1984). A more accurate estimation of marsh slope should be determined that will include consideration of the type of marsh that is being designed and the area under consideration.

Water quality

Salinity and temperature are regulated by tidal flows and freshwater runoff into the wetland. Most salt marsh plants can tolerate salinities of up to 30 to 40 parts per thousand (ppt) (Zedler 1984; U.S. Army Corps 1978; Harvey et al. 1983). At times, especially in Southern California lagoons and marshes, salinities can become much greater than 40 ppt after tidal entrances are closed by littoral transport and evaporation rates increase during the summer months (Zedler et al. 1980). Temperature during times of tidal closure can increase to levels that significantly decrease oxygen solubility. Freshwater runoff is needed in these systems to force the reopening of the ocean entrance. There is a balance that should be met, however, between the inflows of freshwater and saltwater. Reduction in salinity for long periods of time may produce conditions that will encourage the establishment of brackish marsh plants. Under reduced salinity conditions, a variety of brackish water plant species may displace native marsh species and change the character and productivity of the marsh. Models are available that can be used to predict salinity, temperature, and water quality but they require input data from hydrodynamic models. Use of properly calibrated water quality models could provide essential data to avoid creating stagnant water areas, highly saline areas, or areas where pollutants might concentrate

Anthropogenic influences

Human disturbance of marsh environments has greatly affected marsh hydrodynamic processes. Access to areas within and near marshes has necessitated the construction of levees and bridges. Culverts through levees are often used to maintain flow between wetland areas, but their limited cross-section dampens tides and seriously reduces sediment and dissolved material transport (Ferren et al. 1987). Short bridges also serve as barriers to tidal flow. Scour becomes a problem as the water velocity increases where the flow is forced through a narrow opening. Sediment is redeposited on the landward side of the bridge where it accumulates and can eventually seal off outlying areas from tidal effects (Bradshaw 1976). Accumulation of wrack in a breach cut that was too narrow prevented the cutting of a slough through the marsh and the free flow of water through the dike breach at Bracut Marsh near Eureka, California (Josselyn 1988a).

Development of Southern California watersheds and a resulting increase in erosion has increased the occurrence and duration of inlet closures in Southern California (Zedler 1990). Runoff from hillsides and yards transports sediments into the marsh where, under reduced velocities, they settle out and limit the amount of water flowing in and out of the marsh. A large tidal prism is needed to resuspend sediments, clear entrance channels, export excess nutrients, and transport larvae. Sedimentation has also been accelerated within some marshes in Northern California. Sedimentation increased by 45 percent in the Smith River Delta due to upstream logging and road construction (Monroe et al. 1975). Periodic dredging has been necessary to increase flows and provide flood protection in some areas, such as Mugu Lagoon (MacDonald 1976b) and Carpinteria Marsh (Ferren 1985). The presence of upstream water control structures can create sediment shortages that may interfere with restoration projects that rely on natural sedimentation for soil development. Modification and importation of upland soils may be necessary for those projects (see Chapter 4).

Many wetlands, located in large urban areas, receive a considerable inflow of freshwater from storm drains. At times, storm runoff may be their only source of freshwater. Stormwater includes lawn and street runoff and carries potential pollutants such as fertilizers, pesticides, heavy metals, motor oils, and grease. Algal growth and detritus have increased in Carpinteria Marsh as a result of runoff from nearby greenhouses (Ferren 1985). Information is needed on the ultimate fate of pollutants in the marsh (see Chapter 9), to determine if they are converted to less harmful substances or if they are accumulated in plant and animal tissue to the ultimate detriment of the marsh.

RESEARCH NEEDS

Available mathematical models need refining and expansion to generate more accurate physical descriptions of the hydrodynamic processes occurring in salt marshes. Field verification of model results and more precise data collection methods will improve the applicability of such models. Consideration must be given to data acquisition under limited funding and limited time frames. Additional knowledge must be acquired regarding the development of natural drainage patterns and the most efficient sizes, shapes, and distribution of channels. The following items should be considered for future research to increase the understanding of hydrodynamic processes and the effectiveness and applicability of models:

1. Determination of optimal marsh surface and channel characteristics, such as channel slopes, lengths, and widths.
2. Implementation of field and laboratory studies to delineate the physics of flows and sediment transport in marshes, particularly with regards to friction factors for over-marsh and channel flows.
3. Post-construction verification of flow rates, flow patterns, and sedimentation rates predicted by models.
4. Development of economical synoptic measurement techniques to improve the collection of data, such as local tide levels and suspended solids concentrations.
5. Development of more representative models that will include the effects of energy dissipation across the marsh surface utilizing a new approach for the description of fluid resistance.

4
SOIL DEVELOPMENT

Suitable marsh soils are required for plants and benthic organisms, essential links in the marsh food chain, to become established. Mature soils support important chemical reactions that free nutrients for plant use and/or convert pollutants into less harmful compounds.

BACKGROUND

In marsh restoration and creation projects, the necessary marsh soils can be supplied in two ways. In the first method, hydraulic conditions are created that will allow natural sedimentation to occur and allow marsh soils to build up over a period of time. The principal benefit of this type of soil development is that the soils should generally be of high quality for plant growth. However, it may take years for enough sediment to deposit to support marsh vegetation (Josselyn 1988b). In some cases, the amount of sediment available may be sufficient to maintain the marsh, but may be of poor quality (wrong particle sizes, wrong organic content, etc.) and not useful as vegetative substrate. In the second method, marsh soils are created from the soil available at the site or from soils brought to the site from some other location. The latter method of supplying soils is most likely to be used by Caltrans due to time constraints. Imported soils, such as dredged material, are beneficial in that they are available for plant growth immediately. However, in several instances, problem soil conditions have hindered or prevented the establishment of vegetation. Existing soils (non-marsh soils or degraded marsh soils) and imported upland soils may also be useful for salt marsh construction, but their ability to support marsh plant growth is not well understood. When imported soils are used, little is known about the time required for the soils to chemically stabilize and become similar to marsh soils.

In many marsh restoration projects, a combination of the soil supply methods has been used. For example, in Muzzi Marsh (San Francisco Bay), the channels were designed so that about six inches of fresh bay mud would cover the bottom and allow *Spartina foliosa* to become established. Some of the middle and high elevation areas were created using imported soil (dredged material). The low and middle elevation areas within the marsh were colonized by *S. foliosa* and *Salicornia sp.* However, the high elevation areas that were created with the use of imported soil had some problems with vegetation establishment. When anaerobic sediments are drained and exposed to air, the sulfides in the soil are oxidized, concentrations of sulfuric acid increase, and the soil pH is reduced to a level that is too low for most salt marsh plants to grow. In the lower portions of the marsh, where tidal flushing is frequent, the sulfuric acid is usually leached out within a few months and the soil pH increases to acceptable levels. In the higher portions of the marsh, the acid is not leached out quickly and the low pH soil conditions may persist for several years (Josselyn and Buchholz 1984). Marsh restoration and creation requires that proper soils be available to support salt marsh vegetation. Some important issues that should be considered with respect to soil development are discussed below.

ISSUES

If natural soils are desired, it is important to be able to predict sedimentation rates within marshes so that a time table for marsh development can be established. If soils available at the site, or imported soils, are to be used, a variety of conditions should be met to produce a soil suitable for plant growth. Important soil development parameters include soil source, pH, salinity, degree of aeration, nutrient and organic matter content, and pollutant content.

Soil source

Marsh soils may develop naturally due to deposition of suspended sediments or they may be supplied using existing or imported soils. When existing or imported soils are used, it may be necessary to modify the soils in some manner to enable the soils to support salt marsh plants without a long period of maturation.

Natural deposition. In salt marsh restoration and creation projects, it may be desirable to allow natural deposition of sediments to occur as opposed to using modified or imported soils. Natural deposition would result in soils with the proper characteristics (particle size, pH, salinity, etc.) for plant growth and would eliminate the problem of having to manipulate poor quality soils that are often used for fill material. It is possible to predict sedimentation rates using sedimentation models (see Chapter 3). However, more field data are needed to verify the reliability of existing models. Unfortunately, in some cases there may not be a sufficient supply of suspended sediment for natural deposits to form within a desired time.

Soil modification. If a marsh is to be created from an upland site, existing or imported soils are often used. Using existing or imported upland soils would require some modifications to the soil so that it could support the development of salt marsh plants. The use of upland soils (either existing or imported) in marsh creation is not well documented. If upland soils could be used as marsh soils, the construction process would be simplified considerably (see Chapter 8). However, just what is needed to alter an upland soil to the point where it could support marsh plants immediately is unknown. Marsh soils derived from upland soils would require physical and chemical characteristics similar to those of natural marsh soils and would have to support the same chemical and biological reactions to enable marsh plants to grow successfully.

In some cases, it may be desirable to use dredged material containing silt and clay as the soil source. However, the use of dredged material may lead to problems with acidic soils. In several marsh restoration projects, particularly in the San Francisco Bay area, dredged material has been used to bring the site up to the proper elevation. Because dredged soils often contain high sulfide concentrations, highly acidic soil conditions have developed (Josselyn and Buchholz 1984).

In marsh restoration and enhancement projects, the existing marsh soils may have been degraded and modification may be necessary to rejuvenate the soil. In a marsh restoration project in Hayward, a diked marsh was restored to tidal flow by breaching the dike. Islands were created with former bay muds and those areas maintained very low soil pH conditions (as well as high salt concentrations) that had originated when the soil was first drained (Niesen and Josselyn, ed. 1981). Some of the most important soil parameters that are needed for plant growth are discussed below.

Soil pH

From the discussion above, it is obvious that the pH of the soil is a very important parameter for plant development in salt marshes. The soil pH will also affect many chemical reactions that occur within the marsh sediments. One of the biggest problems in constructing and restoring salt marshes has been the formation of highly acidic soils. Attempts to correct low pH conditions by applying lime (typically as $CaCO_3$), which helps to raise the pH, have shown promise, but proper amounts and application methods are not well defined (Josselyn and Buchholz 1984). Problems with high soil pH conditions have not been documented for salt marsh soils.

Soil salinity

Soil salinity is controlled primarily by evaporation, duration of tidal flooding, salinity of tidal waters, and incidence and amount of rainfall. Salt marsh vegetation is strongly affected by the soil salinity. *Salicornia sp.* is able to tolerate higher salinity levels than most other salt marsh plants, whereas *Spartina foliosa* tends to grow primarily in areas where the soil salinity is close to the concentration of sea water (34 ppt) (Mall 1969; Mahall and Park

1976). *Salicornia sp.* and *Distichlis spicata* (saltgrass) typically colonizes the upper marsh elevations where soil salinities are higher due to evaporation.

In the Hayward Marsh (San Francisco Bay), high sediment salinities are thought to be a significant factor in the lack of vegetative growth. After ten years, the former salt crystalizer ponds are still mostly mudflats (San Francisco Bay Conservation and Development Commission 1988). In Southern California coastal salt marshes, *Spartina foliosa* exhibited stunted growth and mortality in soils where the salinity is greater than 50 ppt (Zedler 1984). In San Diego Bay, *S. foliosa* was planted in soils having salinities greater than 60 ppt. Many of the transplants exhibited signs of stress. However, a large percentage of the transplants retained viable root systems and resprouted when soil salinities were reduced (Winfield 1985, 1987). If soil salinities are allowed to drop for extended periods of time, which can occur where there are wastewater discharges, freshwater marsh species may invade the salt marsh (Zedler et al. 1984).

Soil aeration

Marsh soils are different from upland soils in that they are inundated by water for extended periods of time and in some instances may be continually saturated. The saturated conditions result in the soil having a thin aerobic layer on the soil surface underlain by an anaerobic layer. Diffusion of oxygen in a saturated soil is much slower than oxygen diffusion through an unsaturated soil. The low oxygen diffusion rate in saturated soils leads relatively quickly to anaerobic, or reduced, conditions. The oxidation-reduction (redox) potential is often used to quantify the degree of electrochemical reduction of wetland soils (Mitsch and Gosselink 1986). Several important chemical and biological reactions occur at various redox potentials. The oxidized and reduced forms of several important elements contained in marsh soils, and the approximate ranges of the redox potentials for their transformation are reported in Table 4-1. As mentioned previously, the oxidation of sulfides in anaerobic soils can lead to the formation of sulfuric acid, which can alter the soil pH. The presence of hydrogen sulfide in wetland soils is fairly common and at high concentrations can be toxic to plants and microbes (Mitsch and Gosselink 1986). Ammonia nitrogen in flooded soils is oxidized to nitrite, then to nitrate (nitrification) within the aerobic soil layer. Nitrate in the aerobic layer is either utilized by the marsh vegetation or diffuses down to the anaerobic layer where it is denitrified by microorganisms to elemental nitrogen or nitrous oxide (Patrick and Reddy 1976).

Table 4-1
OXIDIZED AND REDUCED FORMS OF SEVERAL ELEMENTS AND APPROXIMATE REDOX POTENTIALS FOR THEIR TRANSFORMATION[a]

Element	Oxidized form	Reduced Form	Redox potential for transformation[b], mv
Manganese	Mn^{+4}(Manganic)	Mn^{+2} (Manganous)	250 - 150
Iron	Fe^{+3}(Ferric)	Fe^{+2} (Ferrous)	150 - 100
Nitrogen	NO_3^- (Nitrate)	N_2O, N_2, NH_4^+	200 - (- 50)
Sulfur	SO_4^{-2} (Sulfate)	S^{-2} (Sulfide)	(- 75) - (-150)
Carbon	CO_2 (Carbon dioxide)	CH_4 (Methane)	(- 250) - (- 350)

[a] Adapted in part from Mitsch and Gosselink (1986).
[b] Depends on pH value and measurement technique.

The redox potential has been found to be higher in the root zone for *Spartina alterniflora* (an East Coast form of cordgrass) than below the root zone or in unvegetated sediments. *Spartina alterniflora* oxidizes the sediments in which it grows by passive oxygen release and by active metabolic processes. In waterlogged soils, passive oxygen release is inhibited, the redox potential is decreased, and plants are not as productive (Howes et al. 1981).

Nutrients and organic matter

Nitrogen is the most limiting factor in plant growth in most natural plant-soil systems including the salt marsh (Woodhouse et al. 1974). Marsh plants utilize nitrogen in the ammonium ion (NH_4^+) and nitrate (NO_3^-) forms (Mitsch and Gosselink 1986). Phosphorous can also be a limiting nutrient for plant growth in plant-soil systems. However, in salt marshes, phosphorous is not considered a limiting factor because of its relative abundance and biochemical stability (Mitsch and Gosselink 1986).

Nutrients are supplied by freshwater flows through the marsh and by tidal flooding. Tidal flows are also responsible for exporting various quantities of the different nutrients. Valiela and Teal (1979) estimated that tidal exchange accounts for forty percent of the nitrogen exported from a marsh ecosystem. In marsh test plantings, fertilizers are often used to aid plant growth. In Chesapeake Bay, fertilizers containing nitrogen and phosphorous at a ratio of 4.5 to 1 were applied to the soil during the growing season for *Spartina alterniflora*. Increases in net areal production of plant biomass of 135 to 241 percent were observed, depending on the elevation above mean high water (Garbisch et al. 1975).

Organic matter content is important in determining nitrogen-fixation rates. In a study conducted in San Diego Bay, it was found that soil organic carbon, which was positively correlated with total nitrogen, was lower in a four-year-old constructed marsh than in an adjacent natural marsh (Langis et al. in press). Nitrogen-fixation rates increased substantially for both the natural and constructed marshes following the experimental addition of organic matter. Organic matter in the form of glucose stimulated greater increases in nitrogen-fixation rates than Spartina foliosa detritus (Langis et al. in press).

Pollutants

Because salt marshes are located near urban areas, they are often exposed to pollutant inputs that originate from the activities of humans. The potential effects of pollutants and their possible accumulation within marsh systems are considered in Chapter 9.

RESEARCH NEEDS

If soils are to be supplied to a marsh restoration or creation site by natural sedimentation processes, it is important to be able to estimate the rate of sedimentation. At present, prediction techniques and models for natural sedimentation rates in salt marshes are not verified adequately. When using existing and imported soils for fill in marsh restoration and creation projects, the duration and the conditions that are needed for the soils to become as productive as natural marsh soils are unknown. The chemical reactions that occur within marsh soils are understood reasonably well, but their effects on plant species are not understood completely. The following topics need further investigation to improve marsh restoration and creation efforts:

1. Development of methods and techniques that can be used to predict natural soil deposition rates within a marsh site.
2. Development of methods and techniques that can be used to modify the chemical and biological characteristics of existing and imported soils to support the growth of various types of marsh plants.
3. Determination of the time and conditions required for existing and imported soils to become similar to natural marsh soils.
4. Determination of the effects of chemical reactions and pollutants in soils on marsh vegetation.

5
VEGETATION ESTABLISHMENT

Marsh plants support animal species by producing food, cover, and nesting material. Particular plant associations can provide habitat for particular animals and help determine what functional values the marsh will support. Plants can also attenuate wave energy and affect geomorphic processes. Creation of optimum growing conditions based on the requirements of different marsh plant species will help to insure the establishment of vegetation that supports the goals of the restoration project.

BACKGROUND

Many failed salt marsh plantings can be traced to a lack of understanding of the habitat requirements of the introduced salt marsh plants. As an example, an attempt to establish salt marsh plants at Creekside Park in Marin County was hindered due to the utilization of five year old dredge spoil as substrate. Desiccation led to soil compaction and acidic conditions. Areas above tidal influence, such as constructed islands, did not receive tidal flushing that would have helped alleviate the problem. After eight years, plants were just beginning to colonize the upper areas (Josselyn and Buchholz 1984). Similar problems have been observed in the Bracut Marsh restoration project in Eureka, California. Vegetation did not become established on constructed dredge spoil islands due to low pH. Soil compaction and the presence of gravel instead of soft mud in other sections has precluded establishment of *Salicornia sp.* (Josselyn 1988a).

Successful introduction of *Spartina foliosa* in Muzzi marsh, located in northern San Francisco Bay, was due to the provision of favorable conditions for the plant. Natural sedimentation processes were utilized in the design to accumulate about six inches of fresh soft mud, an amount estimated to be advantageous for the establishment of *S. foliosa*. There is much more *Salicornia sp.* present than *S. foliosa*, but *S. foliosa* has colonized the lower elevations and its area is continuing to expand. The time for colonization of *S. foliosa* is two to three times longer than *Salicornia sp.* (Josselyn and Buchholz 1984). Site surveys and test plantings have proven successful in preventing the loss of valuable plant stock. A dredge spoil island was created in south San Diego Bay near Chula Vista, California. After a soil salinity analysis of the site, areas of questionable quality were identified and then tested with a minimum number of plants over two growing seasons.

Dieback and stunted growth of plants were used as indicators of areas that were to be avoided in the final planting scheme (Winfield 1989).

ISSUES

Issues that should be addressed in an effort to deal effectively with the planting and maintenance of marsh vegetation include: environmental factors that affect plant growth, guidelines for plant establishment, young plant protection, control of freshwater inflows, planting to encourage animal colonization, and the effects of urban pressure.

Plant requirements

Elevation, period of inundation, and salinity affect the distribution of salt marsh plants (Mall 1969; Zedler 1982; Harvey et al. 1983). There have been many attempts to subdivide the marsh into distinct elevation zones (Hinde 1954; Vogl 1966; Mahall and Park 1976), however, Zedler and Nordby (1986) describe the distribution of plants in the Tijuana Estuary as a continuum, where "almost every species has its peak occurrence at a different elevation." No clear zones are observed except in the case of *Spartina foliosa* which existed in monotypic stands below levels of 2.3 ft (0.7 m) above mean sea level (Zedler 1977). Vogl (1966) also concluded that wetland species varied continuously from zone to zone in the Upper Newport Bay, with specific species dominating in certain elevational zones. Much research has been done on the requirements of *Spartina sp.* with respect to salinity, nitrogen, phosphorus and metals, but the vast majority is for an East and Gulf Coast variety (*S. alterniflora*). Published information on the growth requirements of *Spartina foliosa* and other California salt marsh plant species is relatively unavailable.

Regional differences exist in the distribution of plant species along the coast and in habitat requirements within individual species. Variations have resulted from the evolution of the species under different environmental conditions. It is important to understand how the species vary with ecoregion and which plants are specific to the locality under consideration for transplantation. *Spartina densiflora*, an exotic variety of cordgrass that is now widely distributed in Humboldt Bay, was planted in Creekside marsh in Marin County. It was thought at the time of introduction that *S. densiflora* would occupy the same niche as *S. foliosa* in the San Francisco Bay. Actually *S. densiflora* occupies an elevation zone just above *S. foliosa* and within the lower reaches of *Salicornia sp.*. There is a concern that the *S. densiflora* may eventually outcompete *Salicornia sp.* in the lower elevations (Josselyn and Buchholz 1984). Common wetland species of the four ecoregions in California are listed in Table 5-1.

Table 5-1
TYPICAL SALT MARSH VEGETATION FOUND IN THE FOUR ECOREGIONS OF CALIFORNIA

Plants	Southern California (Zedler 1982)	Central California (Gerdes et al. 1974; Speth et al. 1970)	San Francisco Bay (Harvey et al. 1983)	Northern California (Shapiro and Assoc. 1980; Josselyn 1988a; Seliskar and Gallagher 1983; Monroe et al. 1975)
Atriplex sp. (saltbush)		✔	✔	✔
Batis maritima (saltwort)	✔	✔		
Distichlis spicata (saltgrass)	✔	✔	✔	✔
Frankenia grandifolia (alkali heath)	✔	✔	✔	
Grindelia humilis (gum plant)			✔	
Grindelia integrifolia (gum plant) (formerly G. stricta)				✔
Jaumea carnosa	✔	✔	✔	✔
Juncus lesuerii (salt rush)				✔
Limonium commune (marsh rosemary)	✔	✔		✔
Salicornia bigelovii (annual pickleweed)	✔		✔	
Salicornia virginica (pickleweed)	✔	✔	✔	✔
Spartina densiflora (chilean cordgrass)			✔	✔
Spartina foliosa (pacific cordgrass)	✔		✔	
Suaeda sp. (sea blite)		✔		
Triglochin concinnum (arrow grass)	✔			
Triglochin maritima (arrow grass)				✔

Guidelines for plant establishment

Specific guidelines are available in various marsh restoration manuals for the establishment of marsh vegetation (Knutson 1977; Harvey et al. 1983; Zedler 1984). The manuals contain detailed methods for planting, acquisition of transplants, and plant propagation. Unfortunately, only *Spartina foliosa* has been used commonly in past projects and, as a result, is the only species that is well documented. Regional differences in establishment techniques are lacking in the available manuals. The manual by Zedler (1984) is applicable to Southern California and the one by Harvey et al. (1983) is applicable to the San Francisco Bay marshes. The manual prepared by Knutson (1977) for the Army Corps of Engineers covers only *S. foliosa* and it is assumed that environmental conditions are the same for every ecoregion of California. A summary of the practical literature available on the establishment of salt marsh vegetation in California is presented in Table 5-2.

Spartina foliosa has been successfully propagated under nursery conditions. Transplantation of *S. foliosa* in California was considered only marginally successful (Race 1985), but has since been shown to work very well at many sites (Josselyn 1990). With respect to establishment of species diversity, most plantings to date have been of *S. foliosa* in hopes that other species will migrate into the area. The strategy has met with only limited success. *Salicornia virginica* is the easiest to establish in this manner, as it will propagate itself if the restoration area is close to other stands of *S. virginica* or if dredged spoil (containing seeds) is used as a substrate (Winfield 1988).

Young plant protection

Proper storage of seedlings during the transplant process is essential to their successful weathering of climate or construction delays. Some success has been achieved with heeling-in *S. foliosa* in the intertidal zone. Heeling-in is the process of temporarily storing seedlings by covering the roots with soil to prevent excessive evaporation. Seneca et al. (1975) observed only a 30 percent loss in growth potential after 10 weeks of similar storage. Knutson (1977) also suggests heeling-in *S. foliosa* for several days in an intertidal area. After transplanting, seedlings should be protected from herbivores, wind and wave action. Direct competitors may have to be removed to increase chances of seedling survival. After eight months of growth, *S. foliosa* was 3.6 times more dense in areas where competitors were removed compared to plantings that were made in unmaintained areas (Zedler 1984). Substrate should be stabilized with dikes or other

Table 5-2
SUMMARY OF SALT MARSH VEGETATION ESTABLISHMENT TECHNIQUES APPLICABLE TO CALIFORNIA SALTWATER MARSH SPECIES

Author	Plant	Salinity[a]	Elevation[b]	Method of Propagation	Time of Year	Fertilizer
Zedler (1990) for S. California	Spartina foliosa	Less than 50 ppt	4-5 ft above MLLW	Cores at 3 ft centers	Anytime	Recommended
Harvey et al (1983) for San Francisco Bay	Spartina foliosa	Less than 30 ppt	3 ft above MLLW to MHW	Plugs at 1.5-2 ft centers	February to April	Not recommended
	Salicornia virginica	30-60 ppt	1 ft below MLLW to 3 ft above MHW	Leave plants near desired area	Anytime	Not recommended
Knutson (1977) and U.S. Army Corps (1978)	Spartina foliosa	10-40 ppt	Between MHHW and MTL[c]	Sprigs at 3 foot centers	Early spring	2:1 Ammonium to phosphate (200 lb/acre)
	Spartina foliosa	10-40 ppt	Between MHHW and MTL[c]	Seeds at 2 gal/acre	February to April	2:1 Ammonium to phosphate (200-300 lb/acre)

[a] ppt = parts per thousand
[b] MLLW = mean lower low water; MTL = mean tide level;
MHHW = mean higher high water; MHW = mean high water
[c] Recommended value is disputed (Josselyn 1990)

Note ft x 0.3408 = m

containment structures, especially if planting is done on newly constructed areas of dredge spoil (U.S. Army Corps of Engineers 1978).

Control of freshwater inflows

Restrictions on tidal flow in an area where freshwater is available has allowed the introduction of freshwater species, such as bulrush and cattails. Brackish plants can move into the ecosystem if salinity is less than 25 ppt (Zedler 1982) and can outcompete saltwater species for space and nutrients. Once freshwater species take a firm hold, they are very difficult to eradicate. Cattails and bulrushes have persisted in the San Diego River Marsh in spite of salinities reaching 25 to 33 ppt (Zedler et al. 1984). In the absence of freshwater competitors, however, some salt marsh vascular plants can survive quite well in freshwater and productivity has been shown to increase with decreasing salinity (Phleger 1971; Zedler et al. 1980). However, there is a limit to the increase in productivity. *Salicornia sp.* has disappeared from areas where the salinity has fallen below 10 ppt (Zedler et al. 1984) and a delay in halophyte seed germination has been observed for salt concentrations of 1-10 ppt (Ungar 1978).

Planting to encourage animal colonization

In many instances, planting goals are designed to encourage colonization by specific animal species (Josselyn 1988b; Josselyn et al. 1989). Animals take advantage of the different characteristics of plants within the marsh environment and have developed lifestyles that are at times totally dependent on the benefits the plants provide. Two endangered species, the clapper rail (California clapper rail in northern California and the light-footed clapper rail in southern California) and the Belding's Savannah Sparrow, are extreme examples of this phenomenon. The clapper rail almost exclusively prefers stands of *Spartina foliosa* for nesting and cover. Clapper rail density is the highest in marshes with the most extensive cordgrass areas (U.S. Fish and Wildlife Service 1977). The light-footed clapper rail population in Tijuana Estuary declined from 38 pairs to zero in response to cordgrass death after inlet closure in 1984 (Zedler and Nordby 1986). Belding's Savannah Sparrow, a State of California endangered bird, spends almost its entire existence in *Salicornia virginica* (Massey 1979). *Salicornia sp.* stands are used for nesting, feeding, cover and perching.

Effects of urban pressure

The pressure of urbanization has affected the distribution and health of salt marsh plants. Coastal wetland acreage in California has decreased significantly over the last one hundred years (Dennis and Marcus 1983). Wetlands have been filled for transportation, commercial, and residential development and dredged for marinas and harbors. A large demand for open space and recreation areas has accompanied urban growth and placed further pressures on the salt marshes. Horseback riding, off-road vehicles, and hiking have damaged plants through trampling and soil compaction.

The close proximity to residential development in some wetland areas has caused the introduction of exotic species, such as ice plant and bermuda grass, to the marsh periphery. Once introduced, exotics can be very persistent. An attempt to remove *Chrysanthemum sp.* from the outskirts of Tijuana Estuary by plowing and reseeding with native species failed. *Chrysanthemum sp.* seeds germinated and reinfested the area (Zedler 1988). Invasive plants are becoming a large problem in Carpinteria Marsh in Ventura County. The giant reed, *Arundo donax*, is affecting channel flow, and four types of ice plant are displacing native plants, such as the endangered salt marsh bird's beak (Ferren 1989).

RESEARCH NEEDS

The knowledge to be gained by site surveys and test plantings combined with data on environmental requirements and planting methods for the various plant species will greatly increase chances for plant survival and consequently the overall success of marsh restoration and creation projects. The following items were found to be insufficiently addressed in the available literature and should be considered for future research:

1. Development of planting guidelines that are specific to the different habitats, species and climates of the four ecoregions of the California coast.
2. Incorporation of monitoring parameters into a site survey regime to determine optimal planting areas or required habitat modifications.
3. Development of site maintenance methods to remove competitors and to protect seedlings from herbivores, wind and waves.
4. Testing of habitat modifications, such as irrigation and fertilization, to provide more favorable growing conditions for transplants or seedlings.
5. Development of germination and nursery techniques for the production of seedlings of salt marsh species other than *Spartina foliosa* and *Salicornia virginica.*
6. Determination of environmentally safe and effective methods of controlling exotic plant species.

6
MONITORING

Crucial information regarding the success, failure or evolution of marsh restoration projects has been unavailable to scientists and planners in the past (Josselyn and Buchholz 1982). Information has been lacking because project monitoring has, in general, not been funded, not been continued for a long enough time, and not generated practical, relevant data (Josselyn et al. 1989). Monitoring results should be made more relevant by coordinating the development of the monitoring program to the initial goals of the project. Specific parameters must be chosen that will provide the marsh manager with information to assess if the marsh restoration is proceeding as desired. The collected information should be transmitted to public institutions for reference use. A wealth of information that could help planners avoid poor restoration procedures and insure the success of restoration projects could be available if effective monitoring programs are devised and implemented, and if the results of the programs are made available to the public.

BACKGROUND

Most wetland restoration projects are for mitigation purposes and, typically, are an added expense to the cost of the original development project. Developers and agencies have been looking for marsh restoration projects that can be built easily and maintained with a minimum of additional involvement. This trend has led to monitoring programs that are poorly conceived and operated . Regulatory agencies will probably begin requiring specific guidelines on the length of monitoring and the creation of self-sustaining marshes. As a result, designers will need to become more aware of potential design problems and restoration plans that have gone awry. An effective monitoring program undertaken before, during, and after restoration can serve as an early warning system for significant habitat problems. Maintenance actions can be initiated in response to changes noted in measured parameters to possibly prevent marsh failure.

ISSUES

The factors that should be considered in the development of effective monitoring programs include: objectives of monitoring program, scope of monitoring program, sampling and analysis, data assessment, appropriate monitoring duration, and adaptability. Each of these topics is considered in the following discussion.

Objectives of monitoring program

Important objectives for monitoring programs include (1) the collection and publication of specific data and information that can be used to design a marsh restoration or creation project, (2) the collection and publication of data that can be used to monitor the results of a restoration project and to provide ample warning of impending problems, and (3) the collection and publication of data that can be used to develop a data base for future marsh restoration and creation projects.

Scope of monitoring program

Specific problems with past monitoring programs have been that they are either too limited in scope or too broad. A limited monitoring program is typified by an assessment of a few parameters in response to concern about a single plant or animal species. A broad-based monitoring program includes sampling and testing of a large number of indicators. Because costs are high, this type of monitoring program has not been met with great favor by developers. A balance should be found between the two extremes to provide useful, pertinent data at a reasonable cost.

A choice of monitoring parameters should be made to consider important marsh processes, warning signs of impending change, and whether restoration goals are being met. Primary parameters such as pH, redox potential, salinity, observations of key plant and animal species, dissolved oxygen, and vegetation distribution should be used as indicators in a routine survey of marsh health. When an abnormal condition is found, secondary parameters such as species counts, and the chemical analyses of water and soil would be used to further delineate the cause of the problem. An effective monitoring program will include indicators considered to be important by ecologists and the public (Zedler 1984). Bird watching, elimination of odors, and improvement of marsh aesthetics are some of the issues of public concern. Addressing these issues will be essential for acceptance of a restoration design. Monitoring parameters suggested by several authors are reported in Table 6-1. It is essential that a thorough marsh characterization be completed prior to restoration work to form a solid basis for marsh design. Comparison of data acquired before and after construction will help to determine the direction of marsh evolution and if design goals are being achieved.

Table 6-1
SUGGESTED MONITORING PROGRAMS FOR MARSH RESTORATION PROJECTS

	Parameters					
Author	Water quality	Flora	Fauna	Geomorphology	Frequency	Length of time
Josselyn and Buchholz (1984)	Tidal Flushing	Aerial photography; mapping of plants; biomass evaluation	Fish utilization; bird surveys and nest utilization; endangered species	Not specified	Depends on parameters; seasonally to annually	Not less than five years
Harvey et al (1983)	Yes (specific parameters were not specified)	Plant survival and growth rates	Not specified	Substrate stabilization; soil characteristics	Not specified	Five years
Zedler (1984)	Toxic compounds; salinity	Cordgrass density; algal cover & predominant types; plant cover & height; plant species composition	Bird use (esp. endangered species); invertebrate composition; fish utilization	Elevations; extent of salt pannes and/or bare ground; substrate size and texture	Depends on parameters; seasonally to annually	Not specified

Sampling and analysis

Location of sampling stations and frequency of sample collection are crucial to the process of acquiring accurate, representative data. The location of sampling stations should be chosen to reflect the character and health of the entire marsh. Areas that are frequented by key species or endangered species will need special consideration. Sample collection frequency should be determined to identify seasonal changes and the indicators of design problems.

Collection methods will have to be determined for the chosen parameters. Composite sampling, where samples are taken over a period of time and combined to produce time-averaged results, is probably the best method for chemical determinations. Grab sampling, when one sample is taken at a particular place and time to get a "snapshot" of that instant, is probably best for biological determinations. Environmental effects of sample collection should also be considered. Some methods are very damaging to the ecosystem, such as the gathering of plant mass to determine primary productivity.

The advantage of using primary parameters for routine monitoring is that the results can be determined rapidly, in the field and with a minimum of instrumentation. Additional analysis using secondary parameters will involve some laboratory work. Sample collection methods must include proper storage techniques for the parameters of interest. Refrigeration, acidification or fixation by chemical addition may be necessary to preserve the integrity of the sample until analysis can be completed. Procedures for preservation and analysis that are applicable to water and sediment samples can be found in *Standard Methods for the Examination of Water and Wastewater* (1989).

Data assessment

The results obtained from a well conceived and executed monitoring program are useless unless they are assessed knowledgeably. Proper interpretation of field data is necessary before prescribing appropriate maintenance procedures. Acceptable rates of change and acceptable levels should be determined for each parameter. Results of monitoring programs should also be made available to wetlands experts to confirm the assessment and to generate a data bank for utilization by planners and decision makers in future restoration projects.

Duration

Monitoring programs should be funded in the planning stage of the restoration project (Josselyn and Buchholz 1982) and continued for a long enough time to assess fully the results of the actions that were undertaken. Exact time frames are difficult to determine, but there appears to be general agreement among wetlands experts that monitoring should continue for at least five years (Josselyn and Buchholz 1984; Harvey et al. 1983; Zedler 1988). The deposition of sediments, establishment of plants, and recolonization of invertebrates are all long-term processes. A time frame should be prescribed that meets budgetary concerns, but provides for a consistent connection to the marsh for a sufficient period of time to assess its restoration.

Adaptability

Monitoring parameters and methods will need to be changed for different types of marshes and ecoregions. Key species and the relationship of the species with their environment will change with the type of marsh system. Development of a monitoring program that is adaptable to different site conditions and needs is advantageous. However, general monitoring parameters should be standardized for comparison purposes. The relevance and usefulness of the acquired data will increase with the ability to compare results to other restoration sites and natural marshes.

RESEARCH NEEDS

The success or failure of a marsh restoration project cannot be determined without a monitoring program that can be used to track the evolution of the marsh system. Monitoring is an important tool that can be used to insure the long-term success of a restoration plan. The incorporation of monitoring prior to restoration will allow for the collection of data that can be used to determine what should be done and the continuation of monitoring after restoration will help determine how successful the actions were. To increase the applicability and usefulness of monitoring programs the following items should be considered for future research:

1. Design of a general monitoring protocol that can be adapted to different types of marshes.
2. Identification of key monitoring parameters for selected types of coastal salt marshes in California.
3. Development of interpretive guidelines to aid in the assessment of monitoring data.
4. Determination of effective sampling frequencies for the key parameters.

7
SPATIAL REQUIREMENTS

The task of planning and designing a marsh has not been studied extensively. Mitigation projects can involve creating a marsh from open water, upland, or restoring lands to tidal action by breaching dikes. Each of these marsh development techniques require special attention by the designer and habitat manager to spatial interrelationships such as geometry, habitat area and location, and buffer zones.

BACKGROUND

Upland, tidal, and open water areas provide habitat for plant and animal species and each area is generally colonized by different species. If the conditions of the mitigation project specify that the habitat of a specific, perhaps endangered, species be created, the marsh designer may need to increase the area of the appropriate habitat type. For example, the California Clapper Rail prefers areas where *Spartina sp.* is abundant (U.S. Fish and Wildlife Service 1977). Charged with the task of improving Clapper Rail habitat, a designer would seek to increase the habitat area at the appropriate elevation to support *Spartina sp.* growth.

ISSUES

Areas of concern regarding spatial requirements in the marsh include marsh geometry, selection of areal habitat distributions, and appropriate buffer zone types and sizes. Although these issues should be addressed on a site specific basis, the limits at which these parameters will impact the probability of project success should be available to the designer. The dependance of spatial requirements on regional characteristics along the coast of California is also recognized but not specifically addressed.

Marsh Geometry

The geometry of a marsh in this context refers to the orientation of the marsh with respect to adjacent bodies of water and the overall size of the marsh. In many instances, marsh geometry will be dictated by available mitigation sites. The task of selecting a mitigation site will improve with a better understanding of limiting conditions imposed by the size and orientation of a salt marsh.

The orientation of a marsh with respect to the adjacent open body of water will affect the slope and hydrodynamics of the marsh. Marshes with a long axis extending inland from the water body will be characterized by having a few long drainage channels and relatively shallow slopes. Alternatively, marshes aligned parallel to the open water may have many short steeply sloped channels. Typically, marsh orientation will be a controlling factor affecting the ability of the designer to provide habitats at specific elevations. The most promising marsh orientation should be determined to assure success of mitigation projects.

Creation of huge salt marshes covering hundreds of acres would probably represent the best mitigation projects from an environmental standpoint. Many different species could be supported and the area could be well insulated from anthropogenic influences on its perimeter. Unfortunately, extensive tracts of land are generally not available for conversion to wetlands. Furthermore, unusually large projects may not be financially feasible. Relatively small sites will probably continue to be selected for restoration and creation of salt marshes. The minimum size of a self-sustaining salt marsh has not been determined. It may be wise to forego several small projects in favor of a single large project if the probability for success is improved.

After selecting the orientation and size of the salt marsh, accurate topographic surveys will be required to complete the design of the marsh. The layout, including the correct elevations for marsh plant establishment, and hydrodynamic analysis of a marsh design are dependent on the availability of adequate topographic maps. The California Coastal Commission (1981) recommends topographic maps with a minimum scale of 1 in. = 200 ft and a minimum contour interval of 5 ft (1.5 m) for wetland design activities. Contour intervals as close as 1 ft (0.3 m) may be more appropriate however, because of the importance of elevation on hydrodynamic processes and vegetation establishment as discussed in Chapter 3 and Chapter 5.

Habitat Distribution

The desired percentage of open water, upland, and tidal habitat should be predetermined. Each habitat type may have a minimum spatial requirement that should be met to assure the success of the project. If the marsh is being designed to attract certain species, the areal and elevation parameters should be adjusted to maximize the desired habitat without jeopardizing the overall stability of the marsh system.

Most waterfowl and marine animals prefer open water to tidal or upland habitat. Although the total area of open water will be influenced strongly by the marsh hydrodynamics, minimum or maximum percentages of open water may be required for a successful system. If the marsh is being designed to mitigate habitat for waterfowl or as juvenile fish nurseries, then more ponds and other open water areas should be provided in the design.

Salt marshes occur in the elevations between mean higher high and mean lower low tide levels. The upper elevations of the salt marsh will be inhabited predominantly by *Salicornia virginica,* while *Spartina foliosa* will colonize areas at the lower elevations (Mahall and Park 1976). In addition, large mudflats may exist in this region. Design of a marsh for a specific plant or animal species will involve creating a topography in which large areas of the appropriate habitats are provided. Marsh design for certain plant species may impose strict elevation limits on the layout as discussed in Chapter 5.

Upland areas and islands can provide a refuge for animals escaping high water during flood events (Chabreck 1988). In addition, the higher elevations slowly change and may become tidal areas in the evolution of a marsh subject to sea level rise (Krone 1985; U.S. Environmental Protection Agency 1989). The presence of uplands can assure a longer lifetime of the newly created habitat and are beneficial to the overall ecological system (Zedler 1984).

Buffer Zone

Salt marsh restoration sites may be adjacent to urban or residential regions. A buffer zone between the sensitive habitat and the populated region is essential for the well being of the wildlife inhabiting the marsh. Protection from domestic animals and isolation from litter and roadside refuse dumping will assure a safer, more pristine environment for the wildlife. The California Coastal Commission (1981) recommends a minimum buffer of 100 ft (30 m) between sensitive environments and small developments such as individual single residences. A "much wider buffer area" is required for substantial developments such as subdivisions or commercial zones.

Although distance provides some separation between anthropogenic activities and the wetland; fences, water barriers, or other obstructions may be required to isolate the two incompatible land uses effectively (Josselyn et al. 1989). Issues such as safety, maintenance, and land availability should be considered along with the needs of the wildlife when selecting the appropriate buffer system layout. A minimum buffer size and appropriate buffer structures or barriers should be determined to help the marsh designer increase protection for the marsh.

RESEARCH NEEDS

Quantification of the appropriate limits for the topographic features of a natural marsh would improve the design of created or restored marshes. Exceeding these limits by arbitrary selection of spatial parameters may yield an unstable environment which could evolve quite differently from the original plan. To improve the layout and design of salt marshes, the following topics need additional research.

1. Determination of the practical minimum size of a self-sustaining salt marsh.
2. Development of a rationale for arriving at the appropriate distribution of upland, tidal, and open water habitats to achieve a self-sustaining salt marsh.
3. Determination of the minimum buffer zone size and type to protect specific marsh uses and values.

CONSTRUCTION AND EQUIPMENT

Construction activities in and around saltwater marshes require special attention to insure that environmental impact is minimized. Equipment used in typical upland construction activities has the potential for causing severe damage to sensitive marsh environments. In addition to obvious immediate damage to flora and fauna, the impact on the environment may extend well beyond the construction schedule. Detrimental changes to soil and hydraulic conditions in the marsh are possible if care is not taken during the construction phase.

BACKGROUND

The range and severity of impacts on the marsh by construction activities has not been documented adequately. The discussion in most research papers on marsh creation, restoration, and enhancement is focused on the achievement of a specific habitat; the actual construction procedure is seldom mentioned. As the number of mitigation projects increases, documented construction procedures are needed. For although construction procedures are not a major element in research papers, they are an important consideration in marsh mitigation projects for both financial and environmental reasons. Construction procedures must be identified and developed on a parallel path with research to insure the success of future marsh mitigation projects.

Selection of appropriate construction procedures will depend on the type of mitigation project. Marsh mitigation projects typically fall into one or more of the following four categories:

1. Marsh enhancement
2. Marsh restoration
3. Modification of upland to marsh
4. Modification of open water to marsh

Construction procedures in each of these categories can involve excavation, importing dry or hydraulic fill, or providing tidal action by breaching dikes or removing other constrictions.

Excavating upland areas to tidal elevations can be done quickly and easily with common construction equipment and standard construction procedures. Unfortunately, standard construction procedures may not be consistent with the development of a suitable environment for marsh establishment. Complications with site dewatering and compaction by heavy equipment are a special concern in marsh construction. Furthermore, soils at greater depths are generally more compact than soils at the surface due to primary and secondary consolidation. Deep excavation may expose soils which are too compact or otherwise of a nature which is unsuitable for plant establishment and growth. Excavation below design elevations coupled with importation of organic soils may be a compensating alternative. Additional research is needed to evaluate the feasibility of this method of wetland mitigation.

Conversion of open water to salt marsh involves placing fill material in open water. A 404 permit will be required from the Army Corp of Engineers for projects of this nature. If dredge spoils are used for fill, care must be taken to insure that the material does not contain toxic concentrations of compounds which could affect the plant or animal communities. Specific soil requirements are discussed in Chapter 4.

Breaching dikes to expose areas to tidal action has been done at Muzzi marsh and other San Francisco Bay marshes. Careful topographic surveys must be completed, and precise construction tolerances must be met to prevent the formation of open bodies of water rather than tidal marshes. Consolidation and desiccation of soils after the dikes were built has caused subsidence in many areas (e.g., Elkhorn Slough) that were once tidal marshes. Restoration of these areas to tidal action requires attention to elevation details during construction and consideration of hydrodynamics as discussed in Chapter 3.

ISSUES

There are numerous issues that must be considered when planning and carrying out marsh construction or restoration. The importance of each issue is dependant on the decisions made before construction begins, and should be specified in the marsh design. Decisions regarding construction procedures, equipment requirements, and equipment impacts all play a role in the eventual success or failure of the project.

Construction Procedures

Mitigation projects typically involve one or more of the following construction procedures:

1. Earthmoving and grading
2. Placement, tilling, aeration, and cultivation of imported soils
3. Channel construction

4. Dredging and dredge material disposal
5. Dike breach or construction
6. Structure placement (prefab) or erection
7. Site dewatering
8. Planting or seeding

The relative importance and the long and short term impacts of each construction procedure on the environment should be quantified. Important questions related to construction procedures that must be addressed include: dry versus wet construction, manual versus mechanical methods, and the use of water versus land based equipment. These issues are discussed in the following paragraphs.

Dry versus wet construction. Construction activities are often simplified by temporary site dewatering. Site dewatering allows the use of readily available equipment in site preparation and eliminates many problems associated with construction under saturated or submerged conditions. A dry construction site can be shaped into the final marsh design quickly and efficiently. However, lowering the water table may cause accelerated consolidation of the soil, aggravate problems with land subsidence, and emission of hydrogen sulfide gas (H_2S). Furthermore, the potential for soil oxidation, discussed in Chapter 4, must be considered. Cost, soil consolidation, and potential for soil oxidation are disadvantages which must be assessed when site dewatering is considered.

Manual versus mechanical construction. Manual approaches may have to be substituted for many operations which have been done traditionally with mechanized equipment. Environmental sensitivity and the potential for damage by equipment must be assessed against the cost and availability of manual labor for operations such as planting, seeding or even earth movement or channel digging.

Water versus land based construction equipment. The use of floating construction equipment is an alternative to land based equipment. Barges, rafts and other buoyant platforms should be evaluated as alternatives to heavy equipment to reduce soil compaction.

Material movement can also be accomplished through the use of hydraulic dredges and should be considered as an alternative to land based earthmoving equipment. The density of soils placed by hydraulic transport is generally lower than the density of soils compacted by heavy earthmoving equipment. Hydraulic transport may therefore be suitable for placement of a layer of topsoil for plant establishment. The effects of hydraulic transport on soil properties need to be quantified. These soils may require drying, cultivation, or the addition of soil amendments to assure their suitability for marshes.

Clamshell and dragline operations are other options for submerged soil construction. The use of draglines is a common method of constructing channels in a marsh (Harrison 1976). Operator experience is a factor where draglines are used for construction projects adjoining undisturbed marsh. A lack of precision in placement of the bucket and load discharge has been observed in inexperienced dragline operators (Ng et al. 1982). Operation of draglines adjacent to undisturbed marsh could be damaging to flora and fauna.

Equipment requirements

The appropriate equipment for use on a construction site is a function of the site conditions and construction procedures. Every job site requires a unique approach which must be determined by the designer, contractor, and construction crew. Construction is by its nature a dynamic process in which the available materials and equipment are pulled together to produce the final design. Recommendations of specific equipment to be used for certain activities may restrict creativity in construction and could limit bidders unnecessarily and increase the job cost. The impact of traditional construction equipment on the marsh environment is generally unknown and must be assessed and made available to designers, contractors and construction personnel. Common construction vehicles and equipment and their possible uses in a marsh environment are summarized in Table 8-1.

Equipment performance factors. Before equipment efficiency or impact can be discussed, specific performance factors must be determined. Various parameters can be used to evaluate or predict the performance of equipment in the marsh. A partial list of some of these parameters has been included below.

1. Weight per unit bearing surface area
2. Traction
3. Chassis ground clearance and wheel diameter
4. Drive system (wheels or tracks)
5. Corrosion resistance

Whether qualitative or quantitative, these parameters should be available from the manufacturer of construction equipment. Equipment should be identified that is useful for marsh construction and restoration using these parameters. Limits should be determined for each parameter at which the vehicle or equipment is considered inefficient or unacceptable for construction of a marsh.

Table 8-1
COMMON CONSTRUCTION VEHICLES AND THEIR POSSIBLE USES IN THE CONSTRUCTION AND RESTORATION OF A MARSH

Classification	Equipment	Marsh Application
Floating	Hydraulic Dredges Clamshell dredges Barges Shallow draft boats	Earthwork Channelizing Dredging Surveying Monitoring
Light Weight	Cars Light trucks Pickup trucks Mini-bulldozers (Bobcats) Small trenchers Off Road Vehicles (2,3 and 4 wheelers) Small tractors	Reconnaissance Surveying Monitoring Delivery of construction supplies On site mobility Planting
Medium Weight	Flat bed trucks Trenching equipment Caterpillars and light-medium bulldozers Backhoes Front-end loaders Grading equipment Drill rigs Tractors Rippers Small cranes with clamshell or dragline Shovels	Site Grading Earthwork Channelizing Levee/ dike construction Levee/ dike breach Delivery of construction supplies Well drilling Planting
Heavy Weight	Dump trucks Water trucks Cement trucks Heavy bulldozers Scrapers Large cranes with clamshell or dragline Pile drivers Drill rigs	Site grading Earthwork Channelizing Dredging Placement of prefab structures Pile driving Well drilling Delivery of construction supplies

Traditional construction equipment. Traditional construction equipment may not be appropriate for marsh enhancement or restoration. The soft, saturated, and organic soils can become a quagmire and many vehicles will operate inefficiently or even become stuck. Vehicle rescue operations often involve heavy equipment and unforeseen maneuvers which damage the marsh. The cost of extrication must be considered as part of the total construction cost. Each of the vehicles identified in Table 8-1 should be evaluated for the parameters listed above and efficiency in the marsh environment.

Special equipment. The inefficiency of traditional equipment for marsh construction operations may justify development of special equipment for use in the marsh. Special equipment has been developed for marsh operations by mosquito control districts and contractors for some marsh projects (Williams 1989; Krone 1982). The equipment should be developed to maximize efficiency and to minimize cost and damage to the environment.

Environmental impacts

The equipment used for marsh creation or restoration should be selected to minimize environmental impact. Obviously, the operation of heavy equipment in the marsh will crush plants and animals and should be minimized. Some less obvious impacts are discussed below.

Compaction. Heavy earthmoving equipment can be a benefit to upland construction sites where compaction is desired. However, this same feature is generally not desired in the marsh. Natural marsh soils are loose and not normally subject to compaction. The use of heavy equipment to develop, enhance or restore a marsh will tend to compact the soil and change its character from natural conditions. The effects of compaction on marsh hydraulics, soil chemistry, and vegetation establishment have not been documented adequately .

Rutting. Ruts are formed as tire tracks from construction or other vehicles moving across the marsh. Rutting may change the elevation enough to restrict plant reestablishment and alter hydraulic flow patterns. Subsequent changes in erosion, sedimentation patterns, and sedimentation rates can be detrimental to the marsh. Movement of equipment across the marsh during construction should be restricted to minimize this impact.

Scarification. Earthmoving equipment used to create a new marsh from an upland area may scarify the soil surface. Similarly a marsh restoration site may become scarified by heavy equipment if the site is dewatered and conventional earthmoving equipment is used.

Bulldozer blades, ditch digging equipment, and other traditional construction equipment create a rougher surface than would be found in a natural channel. Rough surfaces affect the hydraulic friction and influence the hydrodynamics of the marsh. Perhaps even more importantly, the effects of scarification on vegetation establishment and propagation must be considered.

Fluid spills. Several different fluids are used in the operation of mechanized construction equipment. There is a potential for fuel and oil spills in the operation and refueling of equipment in the marsh. Hydraulic lines under pressure have been known to rupture and spray contaminants onto construction sites (Ross 1989). Care must be taken in sensitive marsh environments to minimize spills.

RESEARCH NEEDS

Evaluation of the impacts of construction procedures and equipment in marsh mitigation will help insure the success of the project. It is important to avoid trial and error solutions to construction problems. Unforeseen environmental impacts and the unexpected costs of failure can generate massive budget overruns and negative public relations on even simple projects. Appropriate construction procedures for marsh restoration and creation must be determined. Engineering calculations must be performed and construction schedules must be developed and tested to evaluate the financial and environmental feasibility of specific construction procedures in the marsh. Similarly the best equipment for construction operations in marsh areas must be determined. The following research objectives should be considered for improving marsh construction.

1. Identification of acceptable construction practices for marsh restoration and creation, including:
   a. Use of site dewatering as opposed to working with saturated soils.
   b. Appropriate uses of manual labor as opposed to machines.
   c. Use of buoyant equipment as opposed to land based equipment.
   d. Identification of methods for conversion of upland to marsh.
   e. Identification of changes in essential soil properties as a result of hydraulic transport.
2. Identification of efficient equipment for use in the marsh environment and assessing the need for special equipment.
3. Assessment and cataloguing of the impacts of equipment on the marsh environment.

9
STORMWATER TREATMENT

While the primary function of any restored or created marsh is to reintroduce an extremely valuable resource that has become alarmingly scarce, almost all coastal wetlands inadvertently serve as a form of water treatment for waters entering estuaries or the ocean. Therefore, it is important to understand the mechanisms that enable marshes to treat stormwater runoff and to understand the treatment capacities of salt marshes.

BACKGROUND

Much research has been done on the ability of marshes to assimilate pollutants (Chalmers et al. 1976; Windom 1976, 1977; Teal et al. 1982), but most of the experimental work has been done on freshwater wetlands. Based on the limited research that has been conducted on saltwater marshes, it has been found that they are capable of removing several pollutants. However, it is not clear how much of the pollutants are actually removed and how much of the pollutants are simply being diluted and carried out into the estuary or ocean. It is very likely that salt marshes can and do treat stormwater runoff effectively, but the effects on the marsh ecosystem are not well known.

ISSUES

If salt marshes do remove large percentages of the incoming pollutants, what is the fate of the pollutants? Do they accumulate until they become toxic to plants and animals? What kind of pollutant loading rates can the marshes treat effectively? How much variation in treatment ability is there between different marshes? These and other questions should be answered before building marshes that will have to accommodate stormwater runoff and to gain a better understanding of the effects stormwater runoff has on natural marshes.

Fate of pollutants

There are several pollutant removal mechanisms that exist within a salt marsh, including sedimentation, adsorption, volatilization, oxidation and reduction, and uptake by plants (Chan et al. 1981). The ultimate fate of the pollutants is not clear. In some cases, salt marshes may serve as a sink for pollutants flowing through the marsh, which helps protect the estuary. However, pollutants may build up within the soil and vegetation to a point where they become toxic to the plants and animals that inhabit the marsh (Kadlec and Kadlec 1978). Animals within the marsh may accumulate toxic chemicals in their tissues, which may in turn be consumed by humans. The fate and consequences of the pollutants leaving the marsh are also not well known.

Pollutant loading

Although several studies have been conducted to determine the treatment capacities of marshes (Chalmers et al. 1976; Tilton 1977), very few of these studies have been done on salt marshes and no standard techniques have been developed to determine the pollutant loading rates that a given marsh can handle. Many different pollutants can be found in stormwater runoff and and their influent concentrations can vary greatly depending on the location of the marsh in relation to urban development, the time of the year and other factors.

Because most of the existing coastal salt marshes in California are located near large urban areas and will be subjected to some stormwater runoff, it is very important that the effects of the pollutants on the marshes are understood. Different marshes are subject to varying types and concentrations of pollutants depending on which pollutants are generated in specific urban areas. Knowledge of the potential pollutant loads and their effects on marshes will enable marsh designers to make better decisions when restoring and creating marshes (Josselyn et al. 1989).

Treatment ability of different marshes

Different marshes contain different vegetation types and distribution patterns, which will have an effect on the ability of the marsh to treat stormwater runoff. The average length of time that it takes for the water to move through the marsh (contact time) is an important factor in determining the amount of pollutant removal (Chan et al. 1981). Knowing what types of marsh vegetation and what types of vegetation arrangements assimilate different chemicals most effectively could be used to enhance marsh restoration and creation projects.

RESEARCH NEEDS

The ability of coastal salt marshes to treat urban stormwater runoff is not well known and the research opportunities are numerous. The following topics need further investigation to improve understanding of salt marsh systems and aid in salt marsh restoration decision-making:

1. Generation of detailed information concerning the fate of pollutants entering a salt marsh.
2. Determination of the inter-relationships between the assimilative capacities of marshes, the rate of sediment deposition within marshes, and the rate of marsh plant growth.
3. Determination of the optimum marsh arrangements for pollutant removal.

10
SUMMARY

Saltwater marshes constitute an important resource and an extremely endangered coastal habitat of California. If the coastal marshes of California are to be preserved, it is no longer possible or acceptable to rely on the results of the extensive research that has been conducted on salt marshes along the gulf and east coast of the United States. Data from local marshes must be available if the creation, preservation, and enhancement of this habitat along the California coast is to be a viable undertaking. A positive beginning has been achieved in California salt marsh research, however, more questions have been raised than have been answered. Many of these questions can be answered and should be answered by additional research. The achievement of successful mitigation by marsh creation in California cannot succeed without a foundation of knowledge which applies to Pacific Coast marshes.

The dynamics of Pacific Coast salt marsh environments involve the interaction of physical, chemical, and biological processes in a complex manner which is essential for the survival of many species. Avian, terrestrial, and marine animals find habitat and forage among a variety of salt marsh plant species. The success of a salt marsh depends on the establishment of this ecosystem which in turns depends on a variety of conditions and processes. Based on a careful review of the literature dealing with marshes with special emphasis on the coastal marshes of California, the following seven areas have been established as the most critical for future research.

1. Hydrological processes
2. Soil conditions
3. Vegetation establishment
4. Monitoring
5. Spatial Requirements
6. Equipment
7. Stormwater Treatment

Understanding the natural processes which affect the evolution of the marsh and the ability of humans to recreate and maintain the ecosystem is an important responsibility. Acceptance of this responsibility is not optional if the successful establishment of salt marsh ecosystems is to occur in the future.

Bradshaw, J. (1976), "The Natural Resources of Agua Hedionda Lagoon," Coastal Wetland Series No. 16, California Department of Fish and Game.

California Coastal Commission (1981), "Statewide Interpretive Guideline for Wetlands and Other Wet Environmentally Sensitive Habitat Areas," adopted by California Coastal Commission.

Chabreck, R.A. (1988), *Coastal Marshes*, University of Minnesota Press, Minneapolis, Minnesota.

Chalmers, A.G., E.B. Haines and B.F. Sherr (1976), "Capacity of a Spartina Salt Marsh to Assimilate Nitrogen from Secondarily Treated Sewage," Report No. ERC 0776, Georgia Environmental Resources Center, Atlanta, Georgia.

Chan, E., T.A. Bursztynsky, N. Hantzsche, and Y.J. Litwin (1981), "The Use of Wetlands for Water Pollution Control," Municipal Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnnati, Ohio.

Clark, J.R. (1983), *Coastal Ecosystem Management*, Robert F. Krieger Publishing Co., Malabar, Florida.

Coats, R., C. Farrington, and P. Williams (1987), "Enhancing Diked Wetlands in Coastal California," In O.T. Magoon et al. (eds.), *Proceedings of the Fifth Symposium on Coastal and Ocean Management (Coastal Zone '87)*, vol. 4, pp. 3688-3700, American Society of Civil Engineers, New York.

Collins, L.M., J.N. Collins, and L.B. Leopold (1987), "Geomorphic Processes of an Estuarine Marsh: Preliminary Results and Hypotheses," In V. Gardiner (ed.), *International Geomorphology 1986 Part I*, John Wiley & Sons, New York, New York.

Dennis, N.B. and M.L. Marcus (1983), "Status and Trends of California Wetlands," ESA/Madrone, Novato, California.

Ferren, W. P. (1985), "Carpinteria Salt Marsh, Environment, History, and Botanical Resouces of a Southern California Estuary," Publication No. 4, The Herbarium, University of California, Santa Barbara.

Ferren, W. P., D.G. Caprale and D. Hickson (1987), "University of California, Santa Barbara Campus Wetlands Management Plan. Part I - Technological Report on the Botanical Resources of West and Storke Campuses," Environmental Report No. 12, The Herbarium, University of California, Santa Barbara.

Ferren, W.P. (1989), University of California, Santa Barbara, Personal Communication.

Garbisch, E.W., Jr., P.B. Woller, and R.J. McCallum (1975), "Salt Marsh Establishment and Development," Technical Memorandum No. 52, U.S. Army Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Virginia.

Gerdes, G.L., E.R.J. Primbs, and B.M. Browning (1974), "The Natural Resources of Morro Bay: Their Status and Future," Coastal Wetland Series No. 8, California Department of Fish and Game.

Haltiner, J. and P.B. Williams (1987), "Hydraulic Design in Salt Marsh Restoration," In J.A. Kusler and G. Brooks (eds.), *National Symposium on Wetland Hydrology*, ASWM Technical Report No. 6, Sponsored by the national Wetland Technical Council and the Association of State Wetland Managers, Bernee, New York.

Harrison, J.G. (1976), "Wetlands for Waterfowl," Council of Europe's Information Centre for Nature Conservation, Strasbourg.

Harvey, H.T., P. Williams, J. Haltiner, Madrone Associates, and San Francisco Bay Conservation and Development Commission (1983), "Guidelines for Enhancement and Restoration of Diked Historic Baylands," A Technical Report Prepared for the San Francisco Bay Conservation and Development Commission, San Francisco, California.

Hinde, H.P. (1954), "The Vertical Distribution of Salt Marsh Phanerograms in Relation to Tide Levels," *Ecological Monographs*, vol. 24, pp. 209-225.

Howes, B.L., R.W. Howarth, J.M. Teal, and I. Valiela (1981), "Oxidation-Reduction Potentials in a Salt Marsh: Spatial Patterns and Interactions with Primary Production," *Limnology and Oceanography*, vol. 26, pp. 350-360.

Josselyn, M. and J. Buchholz (1982), "Summary of Past Wetland Restoration Projects in California," In M. Josselyn (ed.), *Wetlands Restoration and Enhancement in California*, pp. 1-10, Report No. T-CSGCP-007, California Sea Grant College Program, California State University, Hayward, California.

Josselyn, M. and J. Buchholz (1984), "Marsh Design in San Francisco Bay: A Guide to Design and Planning," Technical Report No. 3, Tiburon Center for Environmental Studies, San Francisco State University, Tiburon, California.

Josselyn, M. (1988a), "Bracut Wetland Mitigation Bank, Biological Monitoring: 1987, Final Report," State Coastal Conservancy, Oakland, California.

Josselyn, M. (1988b), "Effectiveness of Coastal Wetland Restoration: California," In J.A. Kusler, M.L. Quammen, and G Brooks (eds.), *Proceedings of the National Wetland Symposium: Mitigation of Impacts and Losses*, pp 246-251, ASWM Technical Report #3, Association of State Wetland Managers, Berne, New York.

Josselyn, M., J. Zedler, and T. Griswold (1989), "Wetland Mitigation Along the Pacific Coast of the United States," In J.A. Kusler and M.E. Kentula (eds.), Wetland Creation and Restoration: The Status of the Science, Volume I: Regional Reviews, pp. 1-35, U.S. Environmental Protection Agency, Environmental Research Laboratory, Corvallis, Oregon.

Josselyn, M. (1990), San Francisco State University, Personal Communication.

Kadlec, R.H. and J.A. Kadlec (1978), "Wetlands and Water Quality," In P.E. Greeson, J.R. Clark, and J.E. Clark (eds.), *Wetland Functions and Values: The State of Our Understanding*, pp. 436-456, American Water Resources Association, Minneapolis, Minnesota.

Knutson, P.L. (1977), "Planting Guidelines for Marsh Development and Bank Stabilization," Technical Report No. 77-3, U.S. Army Corps of Engineers Coastal Engineering Research Center, Fort Belvoir, Virginia.

Krone, R.B. (1982), "Engineering Wetlands: Circulation, Sedimentation, and Water Quality," In M. Josselyn (ed.), *Wetlands Restoration and Enhancement in California*, pp. 53-58, Report No. T-CSGCP-007, California Sea Grant College Program, California State University, Hayward, California.

Krone, R.B. (1985), "Simulation of Marsh Growth Under Rising Sea Levels," Proceedings of the ASCE Special Conference on Hydraulics and Hydrology in the Small Computer Age, Orlando, Florida.

Langis, R., M. Zalejko, and J.B. Zedler (in press), "Nitrogen Assessments in a Constructed and a Natural Salt Marsh of San Diego Bay, California," Ecological Applications.

MacDonald, K.B. (1976a), "The Natural Resources of Carpinteria Marsh, Their Status and Future," Coastal Wetland Series No. 13, California Department of Fish and Game.

MacDonald, K.B. (1976b), "The Natural Resources of Mugu Lagoon," Coastal Wetland Series No. 17, California Department of Fish and Game.

Mahall, B.E. and R.B. Park (1976), "The Ecotone Between *Spartina foliosa Trin.* and *Salicornia virginica l.* in Salt Marshes of Northern San Francisco Bay. II. Soil Water and Salinity," *Journal of Ecology*, vol. 64, pp. 811-819.

Mall, R.E. (1969), "Soil-Water-Salt Relationships of Waterfowl Food Plants in the Suisun Marsh of California," *Wildlife Bulletin No. 1*, California Department of Fish and Game.

Massey, B.W. (1979), "Belding's Savannah Sparrow," Southern California Ocean Studies Consortium, California State University Contract No. DACW09-78-C-0008, U.S. Army Corps of Engineers, Los Angeles District.

Mitsch, W.J. and J.G. Gosselink (1986), *Wetlands*, Van Nostrand Reinhold Co., New York, New York.

Monroe, G.M., B.J. Mapes, and P.L. McLaughlin (1975), "Natural Resources of Lake Earl and the Smith River Delta," Coastal Wetland Series No. 10, California Department of Fish and Game.

Mudie, P.J., B. M. Browning, and J. W. Speth (1974), "The Natural Resources of Los Penasquitos Lagoon and Recommendations for Use and Development," Coastal Wetland Series No. 7, California Department of Fish and Game.

Mudie, P.J., B. M. Browning, and J. W. Speth (1976), "The Natural Resources of San Dieguito and Batiquitos Lagoons," Coastal Wetland Series No. 12, California Department of Fish and Game.

National Oceanic and Atmospheric Administration (1988), *Tide Tables 1989, High and Low Water Predictions, West Coast of North and South America, Including the Hawaiian Islands*, U.S. Department of Commerce.

Ng, S.Y., J.C. Rudd, and P.D. Dregger (1982), "Embankment Construction Over Swamp Deposits," In C. J. Schexnayder (ed.), *Proceedings of the Specialty Conference on Construction Equipment & Techniques for the Eighties*, pp. 174-185, American Society of Civil Engineers, New York, New York.

Niesen, T. and M. Josselyn (eds.) (1981), "The Hayward Regional Shoreline Marsh Restoration: Biological Succession During the First Year Following Dike Removal," Technical Report No. 1, Tiburon Center for Environmental Studies, San Francisco State University, Tiburon, California.

Patrick, W.H., Jr. and K.R. Reddy (1976), "Nitrification-Denitrification Reactions in Flooded Soils and Water Bottoms: Dependence on Oxygen Supply and Ammonium Diffusion," *Journal of Environmental Quality*, vol. 5, pp. 469-472.

Pestrong, R. (1965), "The Development of Drainage Patterns on Tidal Marshes," *Geological Sciences, Stanford University Publications*, vol. 10, pp. 1-87, School of Earth Sciences, Stanford University, Palo Alto, California.

Phleger, C.F. (1971), "Effect of Salinity on Growth of a Salt Marsh Grass," *Ecology*, vol. 52, pp. 908-911.

Race, M.S. (1985), "Critique of Present Wetlands Mitigation Policies in the United States Based on an Analysis of Past Restoration Projects in San Francisco Bay," *Environmental Management*, vol. 9, pp. 71-82.

Roig, L. (1989), "A Finite Element Technique for Simulating Flows in Tidal Flats," M.S. Thesis, University of California, Davis.

Ross, M. (1989), Sacramento County Water Resources, Personal Communication.

San Francisco Bay Conservation and Development Commission (1988), "Mitigation: An Analysis of Tideland Restoration Projects in San Francisco Bay," San Francisco Bay Conservation and Development Commission, San Francisco, California.

Seliskar, D.M., and J.L. Gallagher (1983), "The Ecology of Tidal Marshes of the Pacific Northwest Coast: A Community Profile," U.S. Fish and Wildlife Service, Division of Biological Services, Washington, D.C., FWS/OBS-82/32, 65pp.

Seneca, E.D., W.W. Woodhouse, Jr., and S.W. Broome (1975), "Salt-Water Marsh Creation," In L.E. Cronin (ed.), *Estuarine Research, Vol. II, Geology and Engineering*, Academic Press, Inc., New York, New York.

Shapiro and Associates, Inc. (1980), "Humboldt Bay Wetlands Review and Baylands Analysis, Vol. I, II, III," Submitted to the U.S. Army Corps of Engineers, San Francisco District.

Shellhammer, H.S., T.E. Harvey, M.D. Knudsen, and P. Sorensen (1984), "The Salt Marsh Harvest Mouse/California Clapper Rail Recovery Plan," U.S. Fish and Wildlife Service, Portland, Oregon.

Speth, J., R. Fordice, R. Hein, and P. Giguere (1970), "The Natural Resources of Goleta Slough and Recommendations for Use and Development," Coastal Wetland Series No. 2, California Department of Fish and Game.

Standard Methods for the Examination of Water and Wastewater (1989), 17th edition, American Public Health Association, Port City Press, Baltimore, Maryland.

Teal, J.M., A. Giblin, and I. Valiela (1982), "The Fate of Pollutants in American Salt marshes," In B. Gopal, R.E. Turner, R.G. Wetzel, and D.F. Whigham (eds.), *Wetlands: Ecology and Management*, pp. 357-366, National Institute of Ecology and International Scientific Publications, Jaipur, India.

Thomas, W.A., W.H. McAnally, and S.A. Adamec (1985), "User's Manual for the Generalized Computer Progam System, Open-Channel Flow and Sedimentation TABS-2," Waterways Experiment Station, Army Corps of Engineers, Vicksburg, Mississippi.

Tilton, D.L. (1977), "Wastewater Treatment via Wetland Irrigation: Nutrient Dynamics," In C.B. DeWitt and E. Soloway (eds.), *Wetlands Ecology, Values, and Impacts*, pp. 178-197, Institute for Environmental Studies, University of Wisconsin, Madison, Wisconsin.

Ungar (1978), "Halophyte Seed Germination," *Botanical Review*, vol. 44, pp. 2330-264.

U.S. Army Corps of Engineers (1978), "Wetland Habitat Development with Dredged Material: Engineering and Plant Propagation," Technical Report DS-78-16, prepared for Office, Chief of Engineers, U.S. Army, Washington, District of Columbia.

U.S. Environmental Protection Agency (1989), "The Potential Effects of Global Climate Change on the United States," Report to Congress, Office of Policy, Planning and Evaluation, Office of Research and Development, U.S. Environmental Protection Agency.

U.S. Fish and Wildlife Service (1977), "Light-Footed Clapper Rail Recovery Plan," U.S. Fish and Wildlife Service Endangered Species Program, Region 1, Portland, Oregon.

Valiela, I. and J.M. Teal (1979), "The Nitrogen Budget of a Salt Marsh Ecosystem," *Nature*, vol. 280, pp. 652-656.

Vogl, R.J. (1966), "Salt-Marsh Vegetation of Upper Newport Bay, California," *Ecology*, vol. 47, pp. 80-87.

Williams, P. (1989), Philip Williams and Associates, San Francisco, California, Personal Communication.

Windom, H.L. (1976), "Geochemical Interactions of Heavy Metals in Southeastern Salt Marsh Environments," U.S. Environmental Protection Agency, Office of Research and Development, Corvallis Environmental Research Laboratory, Corvallis, Oregon.

Windom, H.L. (1977), "Ability of Salt Marshes to Remove Nutrients and Heavy Metals from Dredged Material Disposal Area Effluents," Technical Report D-77-37, U.S. Army Engineer Waterways Experiment Station, Environmental Laboratory, Vicksburg, Mississippi.

Winfield, T.P. (1985), *Chula Vista Wildlife Reserve Transplant Program*, Prepared for the Port of San Diego.

Winfield, T.P. (1987), "Chula Vista Wildlife Reserve, Transplant Program - Final Report," Prepared for the Port of San Diego.

Winfield, T.P. (1988), "Spring and Fall 1988 Monitoring Surveys of the Marsh Creation Project at the Chula Vista Wildlife Reserve," Letter to Bill Glaser, Port of San Diego.

Winfield, T.P. (1989), Entrix Corp., Walnut Creek, California, Personal Communication.

Woodhouse, W.W., Jr., E.D. Seneca, and S.W. Broome (1974), "Propagation of *Spartina alterniflora* for Substrate Stabilization and Salt Marsh Development," Technical Memorandum No. 46, U.S. Army Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Virginia.

Zedler, J.B. and C.S. Nordby (1986), "The Ecology of Tijuana Estuary, California: An Estuarine Profile," Biological Report 85 (7.5), U.S. Fish and Wildlife Service.

Zedler, J.B. (1977), "Salt Marsh Community Structure in the Tijuana Estuary, California," *Estuarine and Coastal Marine Science*, vol. 5, pp. 39-53.

Zedler, J.B. (1982), "The Ecology of Southern California Coastal Salt Marshes: A Community Profile," U.S. Fish and Wildlife Service.

Zedler, J.B. (1984), "Salt Marsh Restoration, A Guidebook for Southern California," Report No. T-CSGCP-009, California Sea Grant College Program, University of California, La Jolla, California.

Zedler, J.B. (1988), "Salt Marsh Restoration Lessons from California," In J. Cairns, Jr. (ed.), *Rehabilitating Damaged Ecosystems*, vol. I, pp. 124-138, CRC Press, Boca Raton, Florida.

Zedler, J.B. (1990), San Diego State University, Personal communication.

Zedler, J.B., R. Koenigs and W.P. Magdych (1984), "Freshwater Release and Southern California Coastal Wetlands, Technical Report 1: Streamflow for the San Diego and Tijuana Rivers," San Diego Association of Governments, San Diego, California.

Zedler, J.B., T. Winfield, and P. Williams (1980), "Salt Marsh Productivity with Natural and Altered Tidal Circulation," *Oecologia*, vol. 44, pp. 236-240.